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Cumulus Cloud Venting of Mixed Layer Ozone

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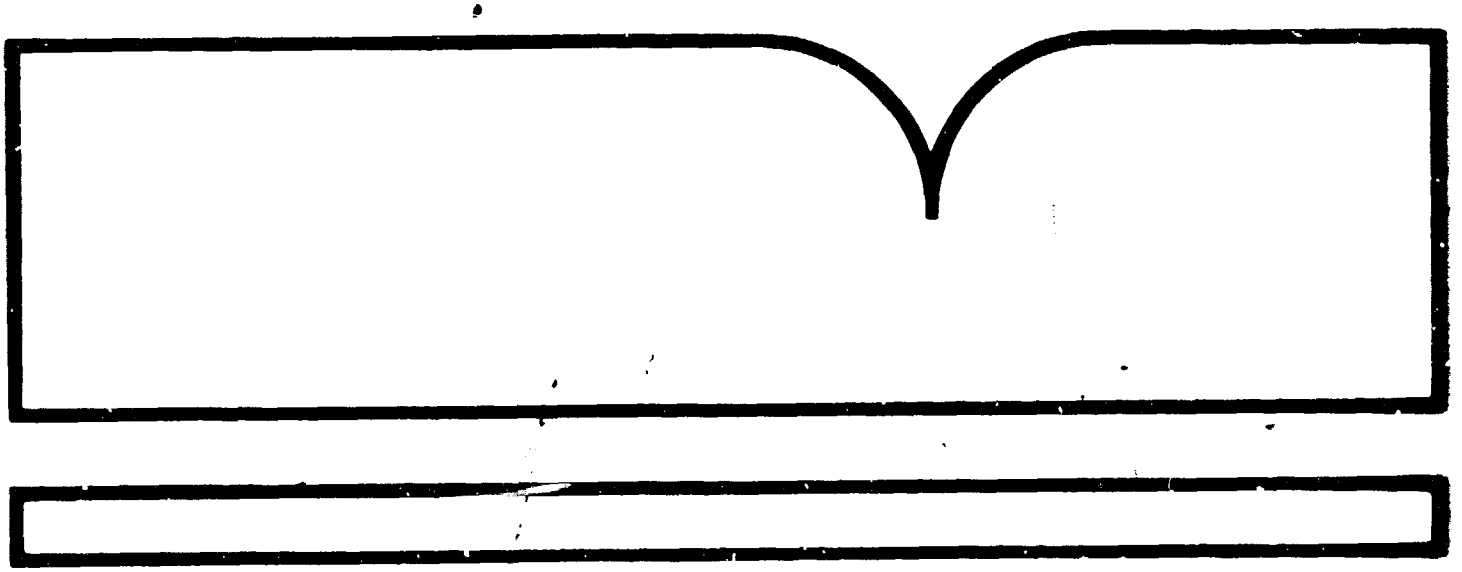

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16. ABSTRACT

Observations are presented which substantiate the hypothesis that significant vertical exchange of ozone and aerosols (and possibly other compounds) occurs between the mixed layer and the free troposphere during cumulus cloud convective activity. The experiments conducted in July 1981, utilized the airborne UV-DIAL (Ultra-Violet Differential Absorption Lidar) system developed by NASA. This system provides simultaneous range resolved ozone concentration and aerosol back scatter profiles with high spatial resolution. Data were obtained during the afternoon along 80 mi East to West and South to North intersecting transects over North Carolina when cumulus clouds were most active, although nonuniformly distributed. Evening transects were obtained in the downwind area where the air mass had been advected. Space-height analyses for the evening flight show the cloud "debris" as patterns of ozone typically in excess of the ambient free tropospheric background. This ozone excess was approximately the value of the concentration difference between the mixed layer and free troposphere determined from independent vertical soundings made by another aircraft in the afternoon.

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Summary

Observations are presented which substantiate the hypothesis that significant vertical exchange of ozone and aerosols (and possibly other compounds) occurs between the mixed layer and the free troposphere during cumulus cloud convective activity. The experiments conducted in July 1981 utilized the airborne UV-DIAL (Ultra-Violet Differential Absorption Lidar) system developed by NASA. This system provides simultaneous range resolved ozone concentration and aerosol backscatter profiles with high spatial resolution. Data were obtained during the afternoon along 130 km east to west and south to north intersecting transects over North Carolina when non-uniformly distributed cumulus clouds were most active. Evening transects were obtained in the downwind region, where the air mass had been advected. Space-height analyses for the evening flight show the cloud "debris" as patterns of ozone typically in excess of the ambient free tropospheric background. This ozone excess was approximately the value of the concentration difference between the mixed layer and free troposphere determined by DIAL and independent vertical soundings made by another aircraft in the afternoon.

1.1 Introduction

This paper provides evidence that photochemical oxidants (and other pollutants) are transported and deposited above the mixed layer by nonprecipitating cumulus convective cloud processes. Conceptually, during periods of strong solar insolation, vigorous rising thermals produce cumulus convective clouds which carry mixed layer air in their updrafts. Some of these clouds can penetrate the inversion at the top of the mixed layer and rise into the free troposphere. These clouds are characteristically short lived, and as they dissipate, mixed layer pollutants are deposited aloft. The net pollutant exchange will depend both on the strength and the areal extent of convective clouds as well as on the

*On assignment from the National Oceanic and Atmospheric Administration, U. S. Department of Commerce.

pollutant concentration differences between the mixed layer and the overlying free troposphere. The US EPA is currently developing a regional scale photochemical oxidant model (6) which addresses the linkage and exchange that occurs between the mixed layer and the overlying free troposphere by cumulus convective processes. Recent studies (1, 3, 4, and 5) provide supporting evidence that this process of cloud venting occurs, and these studies are useful in developing the parametric framework for models. However, there is as yet insufficient observational data to prove that net vertical transport actually occurs from the mixed layer into the free troposphere by cumulus cloud venting. Since cloud activity is highly variable in time and space, an experimental sampling strategy requires highly detailed spatial and temporal resolution of the pollutant fields. Detailed space-height cross sections of ozone (and other pollutants) would provide a suitable analytical base. These measurements are now obtainable from airborne UV-DIAL systems capable of remote and range resolved observations of ozone, aerosols, and other trace gases (2).

The UV-DIAL is a UV differential absorption lidar (DIAL) system consisting of two frequency-doubled Nd:YAG lasers which optically pump two high conversion efficiency tunable dye lasers. The dye lasers are frequency-doubled into the UV. DIAL measurements of ozone are made in the Hartley absorption band with the on-line wavelength nominally set near 286 nm and the off-line wavelength set near 300 nm. The backscattered return signals at these wavelengths are collected by a telescope, detected by photomultiplier tubes, digitized, and stored on magnetic tape. The logarithmic difference between the two backscattered signals is directly proportional to ozone concentration. The UV-DIAL data acquisition system provides real-time calculations of ozone concentration profiles. A more detailed description of the UV-DIAL system is contained in (2).

NASA has successfully developed, demonstrated and deployed the UV-DIAL system on board an Electra aircraft in a number of field studies (2,8). Data for this cloud study was sampled at the rate of 5 profiles/second with a vertical resolution of 15 m for aerosol and 210 m for ozone. Maximum horizontal resolution at a nominal ground speed of 100 m/sec is 20 meters. Confidence in the measurement of ozone concentration is increased by horizontal averaging. The preliminary analysis presented here uses a 25 shot horizontal average corresponding to a horizontal resolution of 500 m.

1.2 Description of the Experiment

This experiment follows and characterizes the pollutant distribution in an air mass known to have experienced active and penetrative cumulus clouds. Pollutants observed to be imbedded in the layer above the top of the mixed layer can then be assumed to be remnants of the dissipated clouds. Such an experiment was conducted by NASA Langley Research Center using the airborne UV-DIAL on board an Electra. On July 22, 1981, the Electra flew two missions over North Carolina, USA. The first mission pattern consisted of along-wind (east to west) and cross-wind (south to north) transects centered over Raleigh/Durham ($35^{\circ}52'N$, $78^{\circ}47'W$) between 1500 and 1600 LDT. Each leg was about 130 km long. The evening mission was located over an area near the Carolina coast which was the projected trajectory of the air mass sampled during the afternoon. The air mass trajectory was subsequently verified by an isentropic analysis. Concurrently, an instrumented Cessna 402 twin engine aircraft provided correlative vertical profiles of ozone (O_3), Bscat (β), temperature (T) and dew point (T_d).

derived from sequential down and up ramp patterns along the same flight coordinates. The Electra cruised at 4 km MSL, and provided lidar data from the surface to 3 km MSL. The Cessna profiles varied from near surface to greater than 3 km MSL. Satellite data and routine NWS/NOAA surface and upper air weather observations were archived for subsequent data analyses.

1.3 Results and Discussion

The mixed layer winds over central North Carolina were generally north-northwesterly, becoming more westerly with altitude. Above the mixed layer, the west-northwest flow backed with height to a westerly flow at 3000 m AGL (Above Ground Level). The wind speed shear was 2.5 m/sec/km. Nonprecipitating penetrative cumulus clouds were active over the sampling area from 1400 to 1700 LDT. Cumulus tops varied from 1.5 km to 4 km AGL. The afternoon soundings of T, T_d, O_3 and β obtained by the Cessna aircraft suggest a mixed layer height of 1600 m. The lapse rate in the mixed layer was adiabatic up to the base of the elevated inversion at 1600 m, and the thermal stratification was stable above. Dew point decreased only slightly within the mixed layer but decreased markedly with altitude above 1600 m. Nephelometer readings indicate some variability in Bscat with altitude and horizontal position. Highest values appear to be associated with the Raleigh-Durham urban plume. However, the Bscat values also exhibit sharp decreases with altitude above 1600 m. The ozone profiles show mean mixed layer ozone of about 80 ppbv, but significant horizontal variations were observed ranging from 75 to greater than 120 ppbv. The latter value appears to be associated with the Raleigh-Durham urban plume. Above the mixed layer, a mean but highly variable ozone concentration of about 70 ppbv was observed; ozone concentrations which correspond to mixed layer values of 80 ppbv were observed when the soundings were taken in the vicinity of the active cloud areas. The evening soundings indicate a lower inversion height suggesting subsidence aloft, and are consistent with a downward motion of approximately 1 cm/sec obtained in the isentropic flow calculation and kinematic calculation from the NWS soundings (7).

Figure 1 displays UV-DIAL observations of aerosol and ozone cross sections. In the top panel (Figure 1a), the lidar backscatter cross section is shown for the south to north transect starting at 1538 LDT and crossing over the Raleigh-Durham airport. Active cumulus clouds attenuate the return signals and appear as white vertical columns. The mixed layer is clearly evident where cumulus convection is relatively inactive, as seen in the southern section at 1540 LDT. The haze is concentrated within the mixed layer, while lighter shading at higher altitudes indicates low aerosol concentrations aloft. On the other hand, the middle and northern segments of the flight contain active cloud convection. The backscatter display suggests a higher mixed layer from 1542 to 1554 LDT in the vicinity of cloud activity. These convective elements literally cloud the issue of defining a mixed layer depth.

The next panel (Figure 1b) depicts the along-wind cross section of aerosol backscatter on the evening flight mission. With the exception of a few isolated clouds, the field of cumulus convection is replaced by layers and patches of aerosol. These layers tilt upward in the vertical from west to east with an average slope of 16 m/km due to wind speed shear. Stronger winds at higher altitudes advect the upper portion of the cloud remnant a greater downwind distance relative to the lower part. Due to a small but non-negligible shear in wind direction, the flight leg only intersects a portion of the tilted cloud remnant.

Figure 1c shows the along-wind ozone concentration cross section measured concurrent with the aerosol display of Figure 1b. The ozone data extends vertically from 1500 to 2500 m MSL. Contour intervals are 10 ppb, and much of the fine detail seen in the aerosol gray scale displays has been smoothed by horizontal and vertical averaging. Ozone concentrations in excess of 70 ppbv are observed to be distributed in layers coincident with the aerosol layers of Figure 1b, with identical tilting due to wind shear. These simultaneous ozone and aerosol scattering measurements are highly correlated in space. These positive ozone concentration anomalies are comparable to the average ozone concentrations observed in the afternoon mixed layer.

It should be emphasized that these vented products are not the result of isolated cumulus events, but represent the integration of many convective intrusions with subsequent injections of aerosol and ozone into the free troposphere throughout the afternoon. From this study it is apparent that intrusive nonprecipitating clouds do deposit mixed layer oxidants and other pollutants above the mixed layer. These injected pollutants exhibit small spatial structure and can now be readily investigated by airborne DIAL systems.

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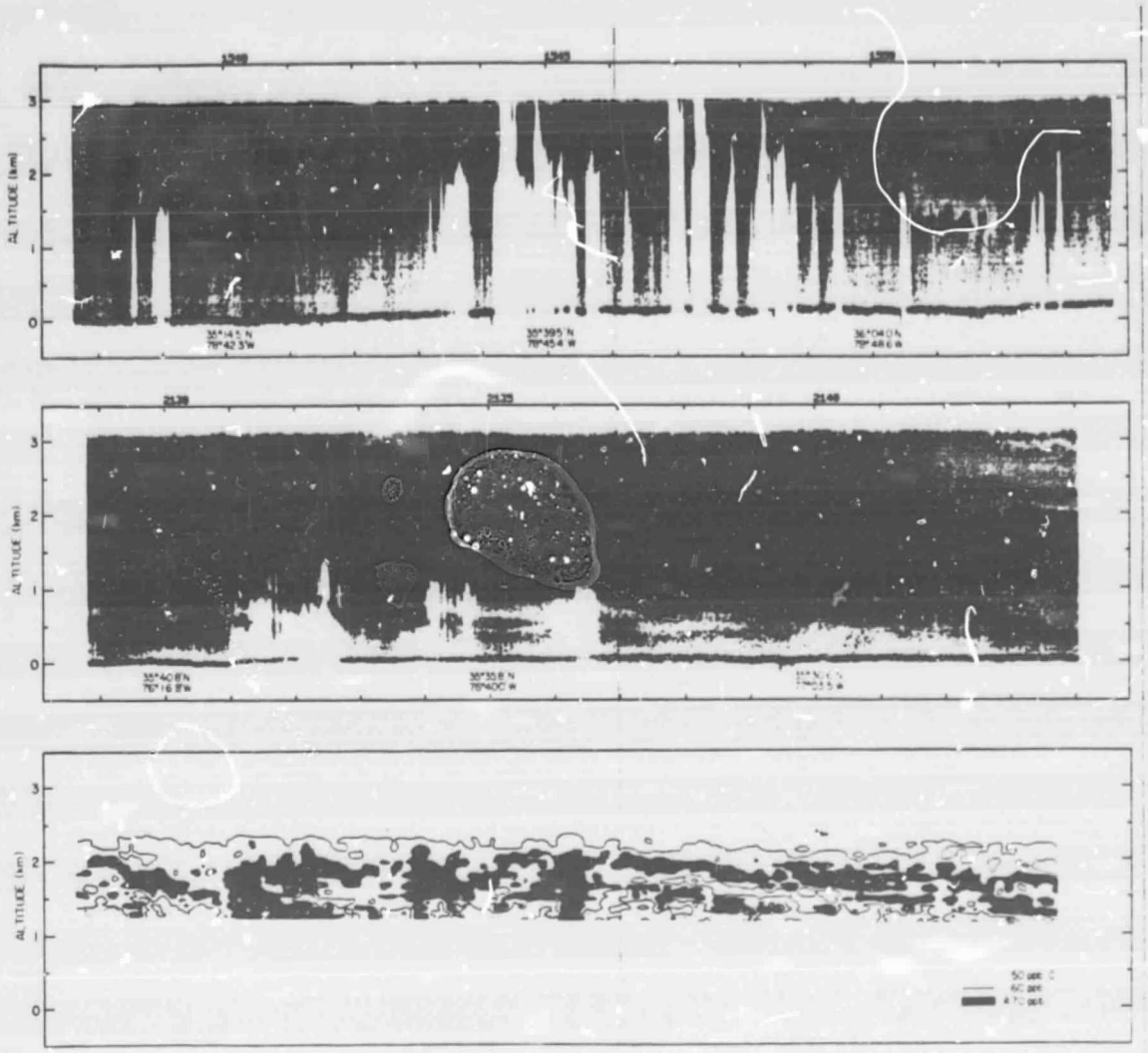

Figure 1.- Airborne lidar observations of aerosol backscattering and ozone concentrations in the same air mass on July 22, 1981 over North Carolina. (a) Cross-wind afternoon cross section of aerosol backscatter; (b) along-wind evening cross section of aerosol backscatter; and (c) along-wind evening ozone concentration cross section measured simultaneous with (b).